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(54) **HEAT ASSISTED MAGNETIC RECORDING WRITE APPARATUS HAVING AN INVERSE TAPERED WAVEGUIDE**

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G11B 5/48 (2006.01)
G11B 5/00 (2006.01)

(52) **U.S. Cl.**

CPC ***G11B 5/4866*** (2013.01); *G11B 2005/0021* (2013.01)

(58) **Field of Classification Search**

None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,170,448 A * 12/1992 Ackley G02B 6/12004 385/131
7,440,660 B1 * 10/2008 Jin B82Y 10/00 369/112.27
7,747,121 B2 * 6/2010 Cho B82Y 10/00 385/129
7,869,309 B2 * 1/2011 Mihalcea G11B 5/1272 360/59
7,885,029 B2 * 2/2011 Miyauchi G11B 5/3116 360/59

(Continued)

OTHER PUBLICATIONS

Notice of Allowance on U.S. Appl. No. 15/216,639, dated Mar. 7, 2017.

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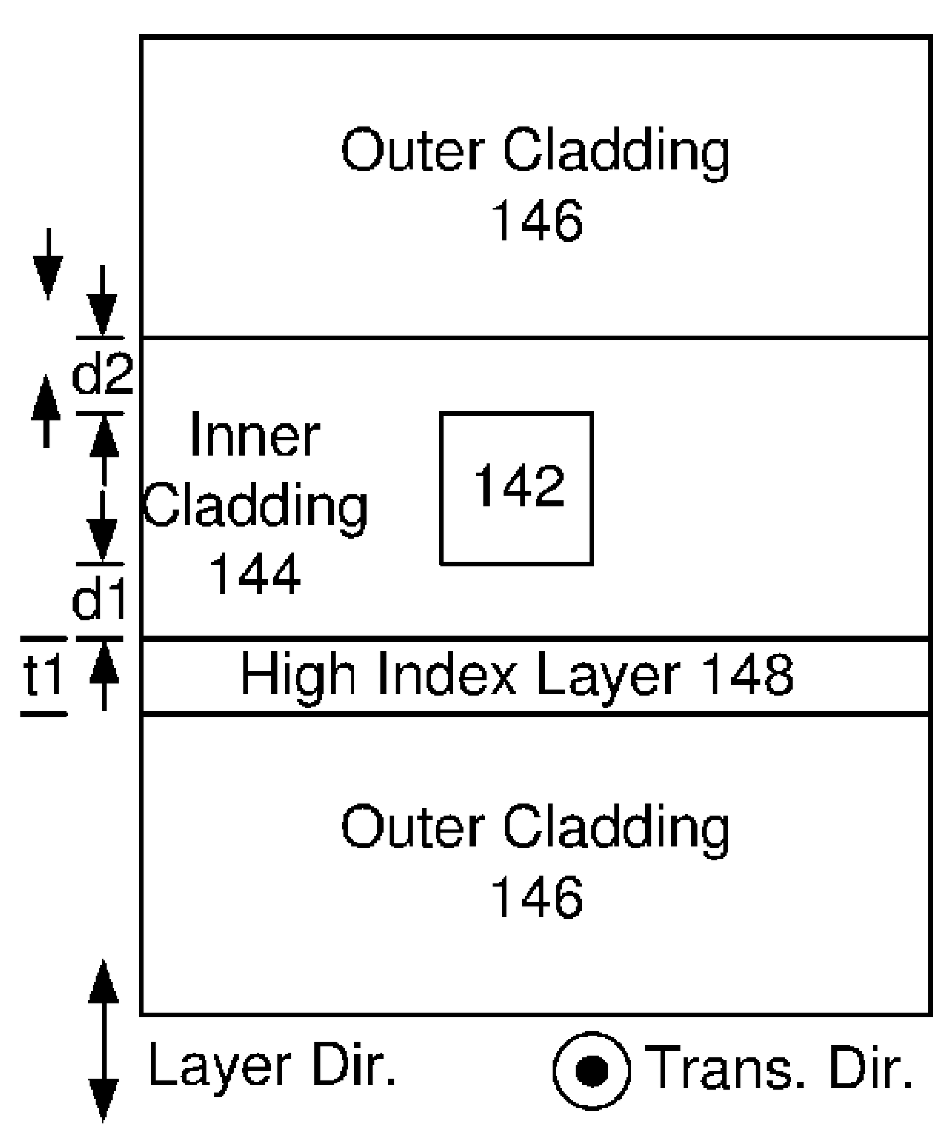
(57) **ABSTRACT**

A heat assisted magnetic recording (HAMR) write apparatus has a media-facing surface (MFS) and includes a pole, coil(s) and a waveguide. The waveguide is optically coupled with a laser and directs energy toward the MFS. The waveguide includes an entrance, a bottom and a mode converter having a core, an inner cladding, high index layer(s) and an outer cladding. The core has sides that diverge in width. The core has a first index of refraction. The outer cladding has a second index of refraction less than the first index of refraction. The inner cladding has a third index of refraction not greater than the second index of refraction. The inner cladding is between the high index layer(s) and the core. The high index layer(s) are between the inner and outer cladding. The high index layer(s) have a high index of refraction greater than the second index of refraction.

20 Claims, 5 Drawing Sheets

100/140/141



(56) **References Cited**

U.S. PATENT DOCUMENTS

8,149,654	B2 *	4/2012	Komura	G11B 5/3116 360/59
8,264,919	B2 *	9/2012	Komura	B82Y 20/00 369/13.13
8,284,635	B2 *	10/2012	Matsumoto	G11B 5/4826 360/125.31
8,400,887	B2 *	3/2013	Iwanabe	G11B 5/314 369/112.27
8,619,511	B1 *	12/2013	Iwanabe	G11B 5/314 369/13.13
8,780,678	B2 *	7/2014	Iwanabe	G11B 5/314 369/13.13
8,923,102	B1 *	12/2014	Shi	G11B 5/314 369/13.32
9,001,628	B1	4/2015	Shi et al.	
9,053,716	B1	6/2015	Matsumoto et al.	
9,111,558	B1	8/2015	Krichevsky et al.	
9,147,415	B2	9/2015	Clinton et al.	
9,280,994	B1 *	3/2016	Iwanabe	G11B 5/4866
9,336,814	B1	5/2016	Shi et al.	
9,632,242	B2 *	4/2017	Peng	G02B 6/1228
9,697,854	B1 *	7/2017	Morelli	G11B 5/314
2004/0008591	A1 *	1/2004	Johns	G11B 5/127 369/13.14
2004/0081033	A1 *	4/2004	Arieli	G11B 7/08 369/18
2012/0327751	A1 *	12/2012	Iwanabe	G11B 5/314 369/13.02
2015/0010266	A1	1/2015	Webster et al.	
2015/0293299	A1	10/2015	Xu et al.	
2015/0316720	A1	11/2015	Yang et al.	
2016/0041340	A1	2/2016	Shi et al.	

* cited by examiner

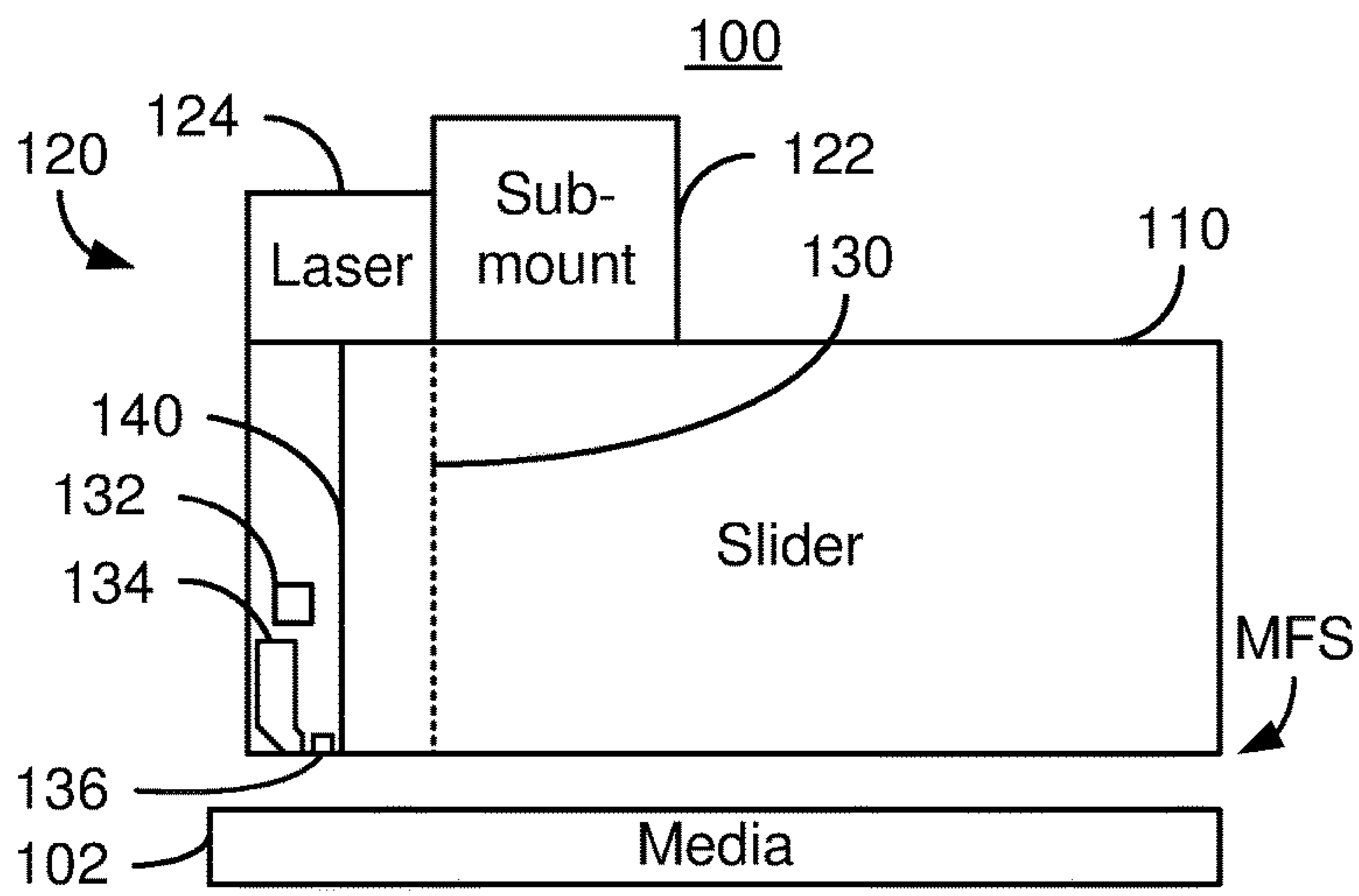


FIG. 1A

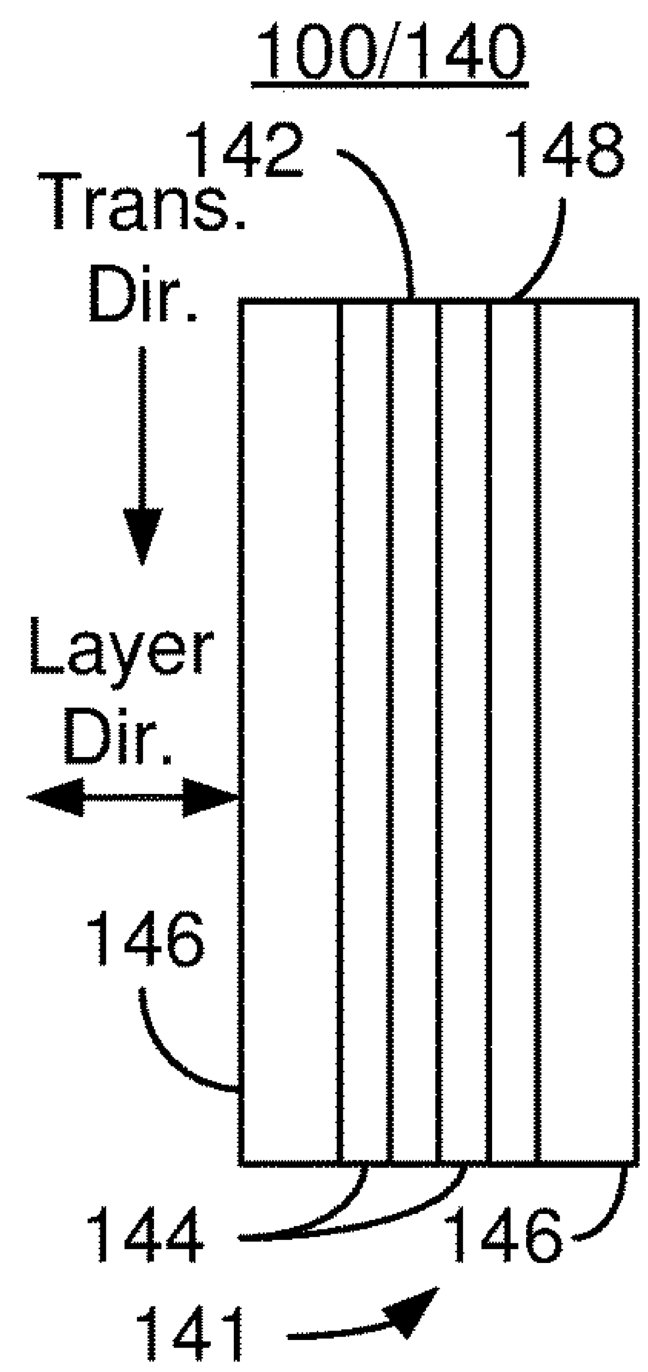


FIG. 1B

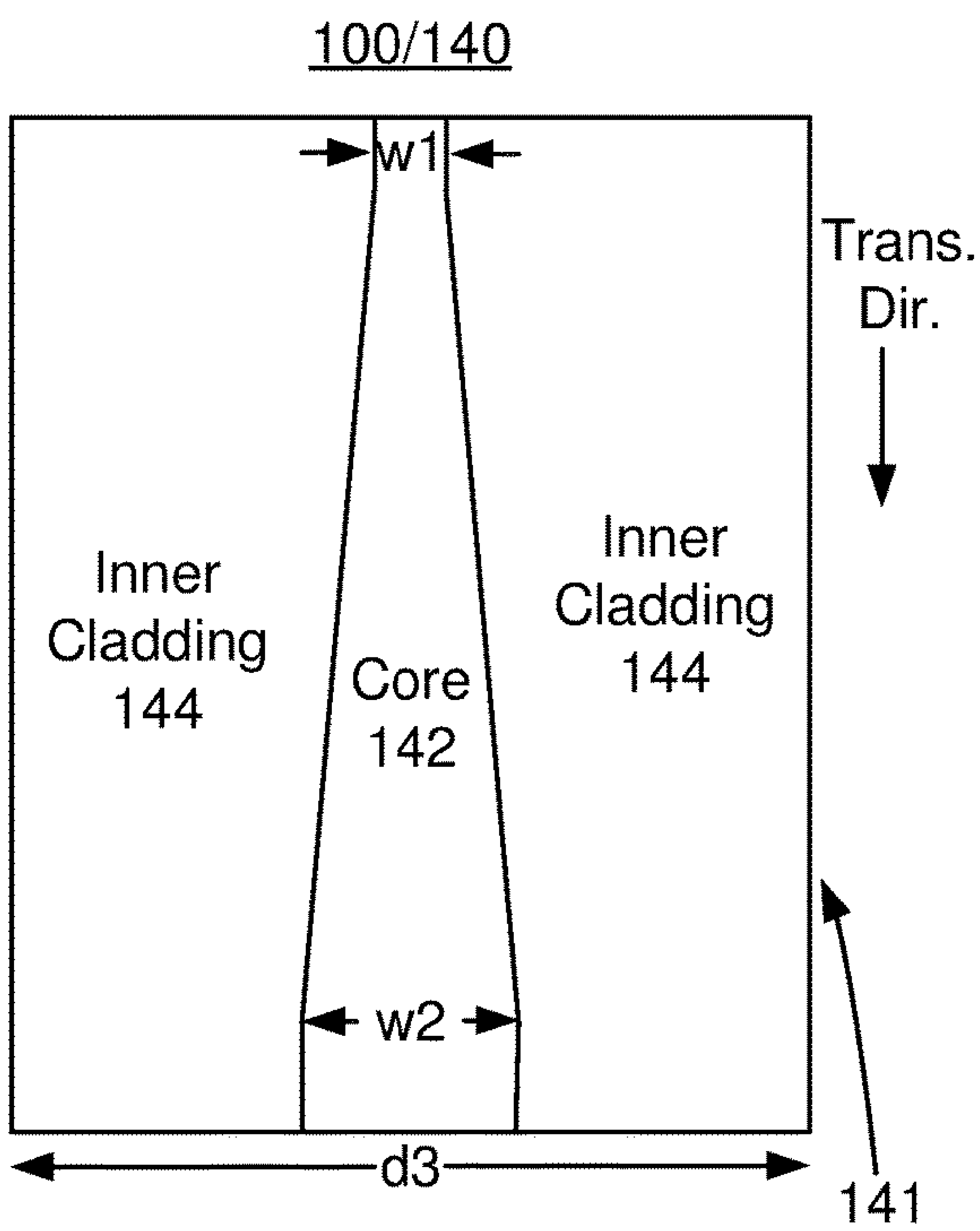


FIG. 1C

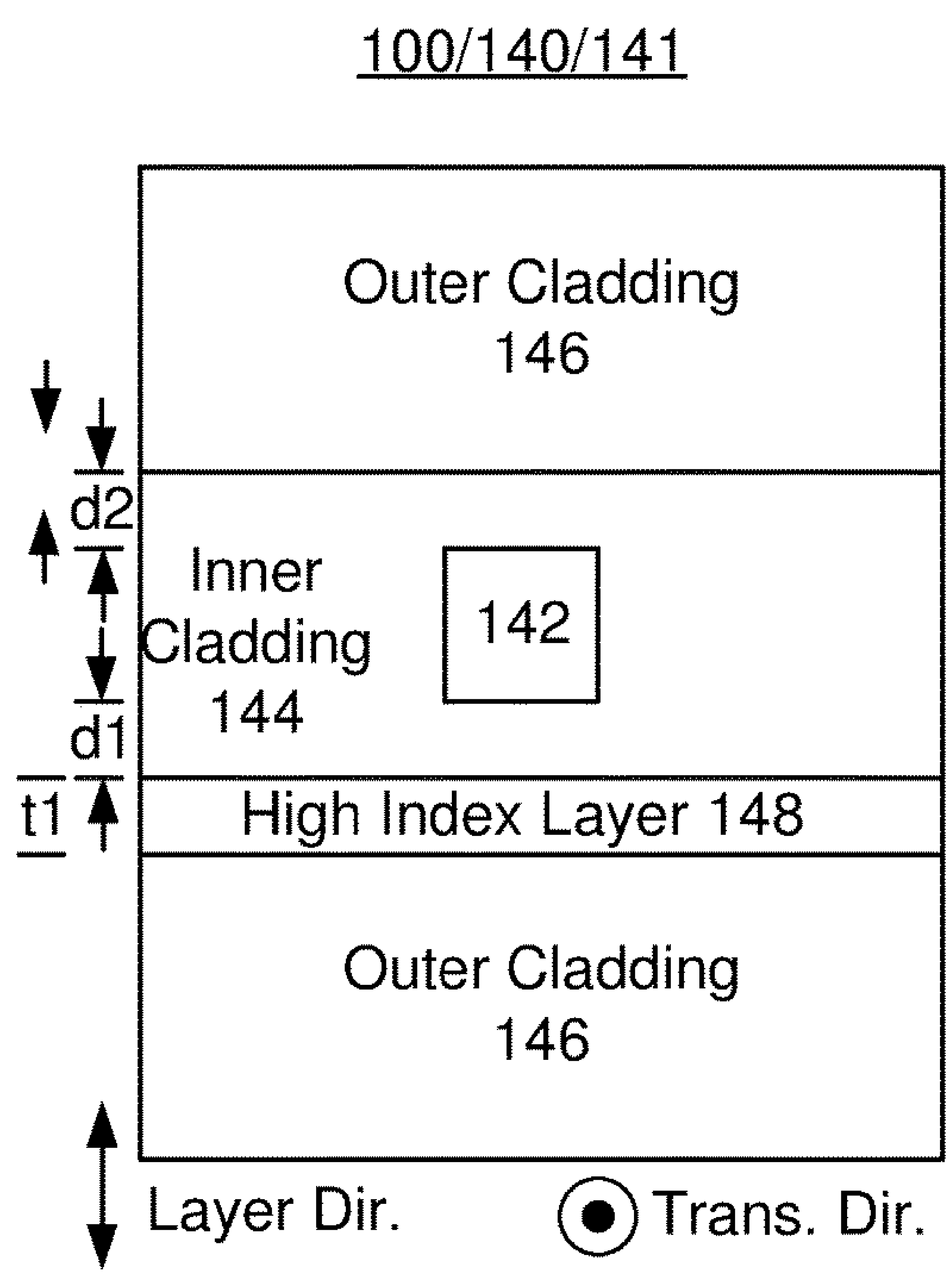


FIG. 1D

100'/130'/140'

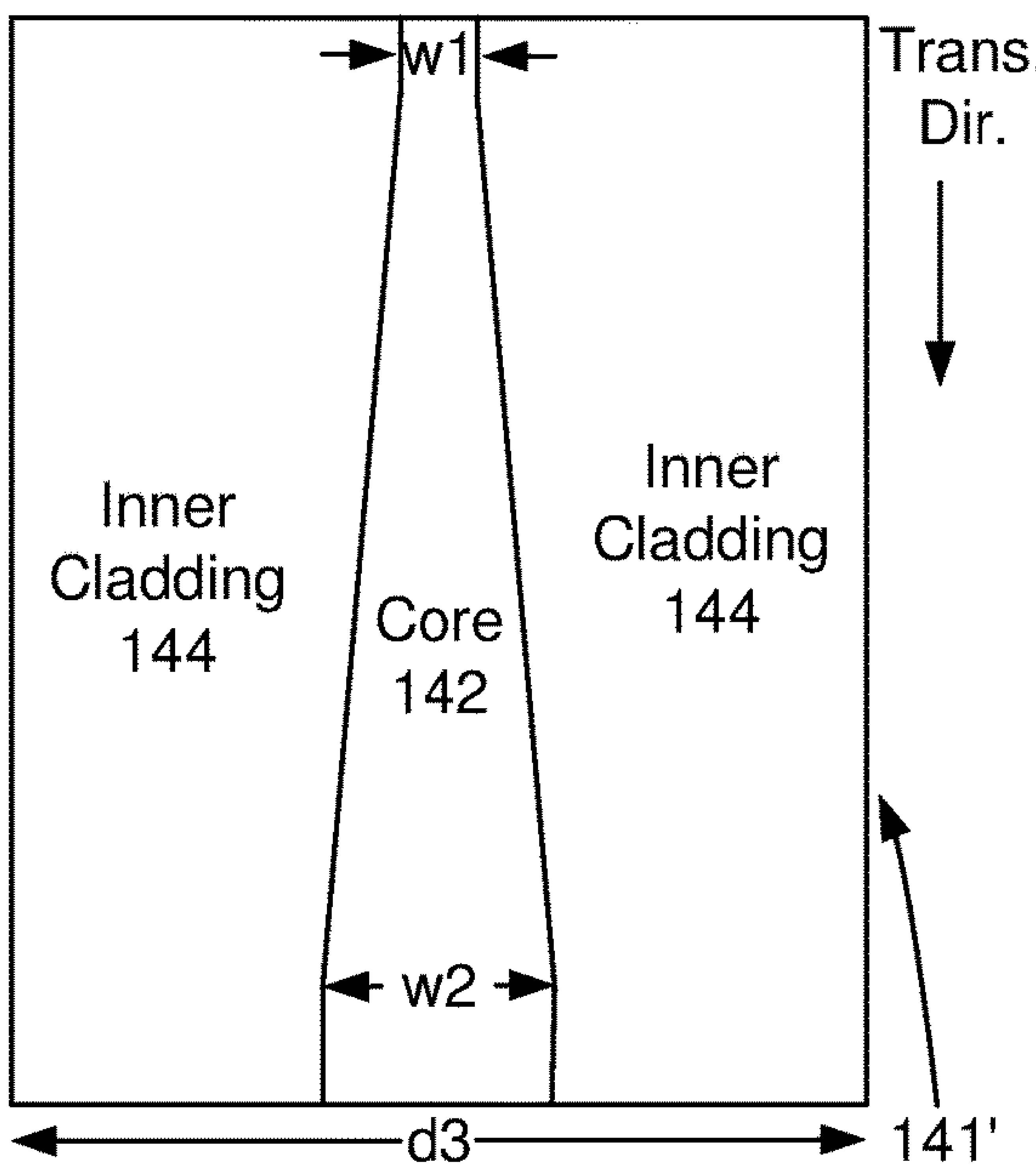


FIG. 2A

140'/141'

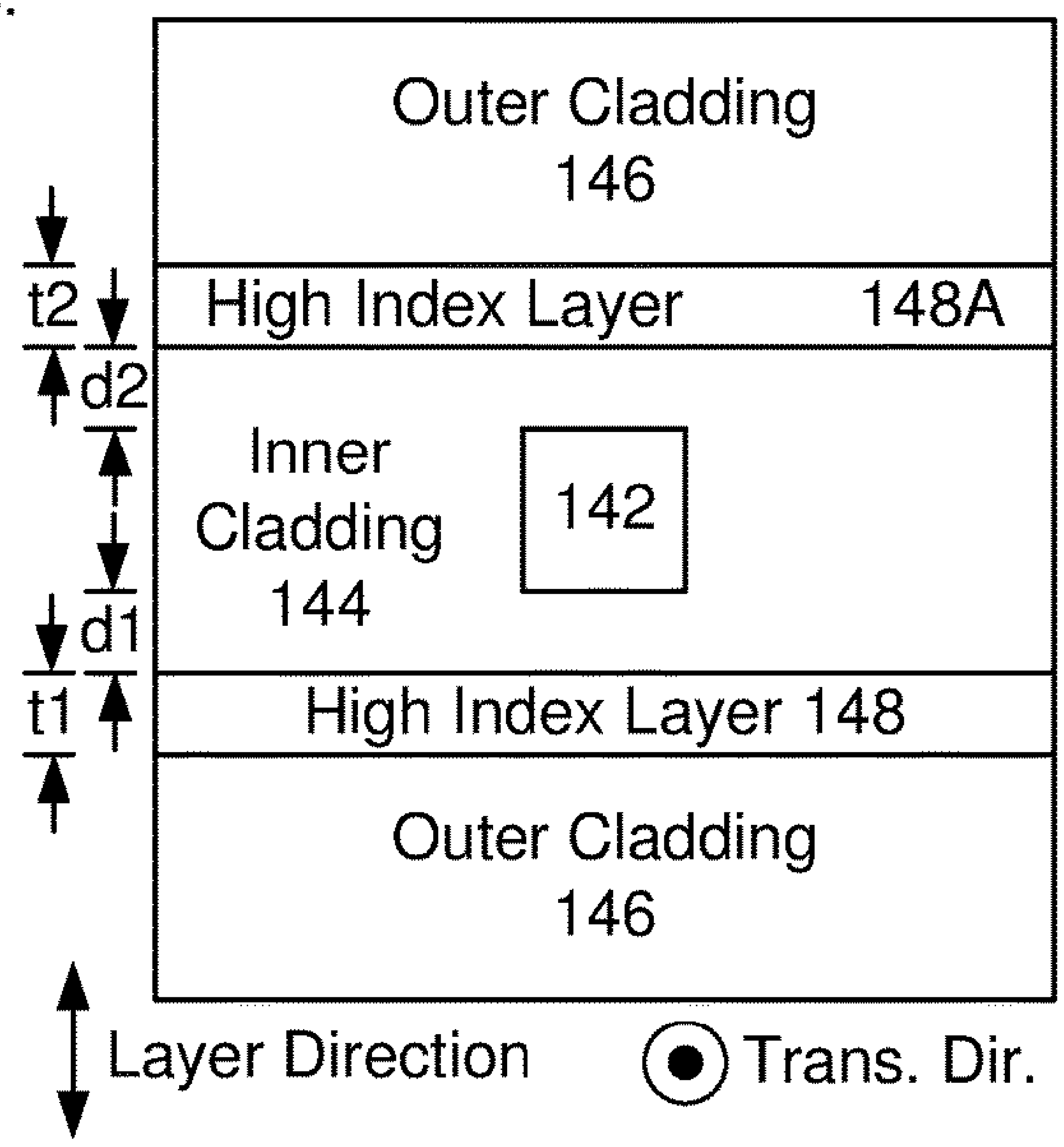


FIG. 2B

100"/130"/140"

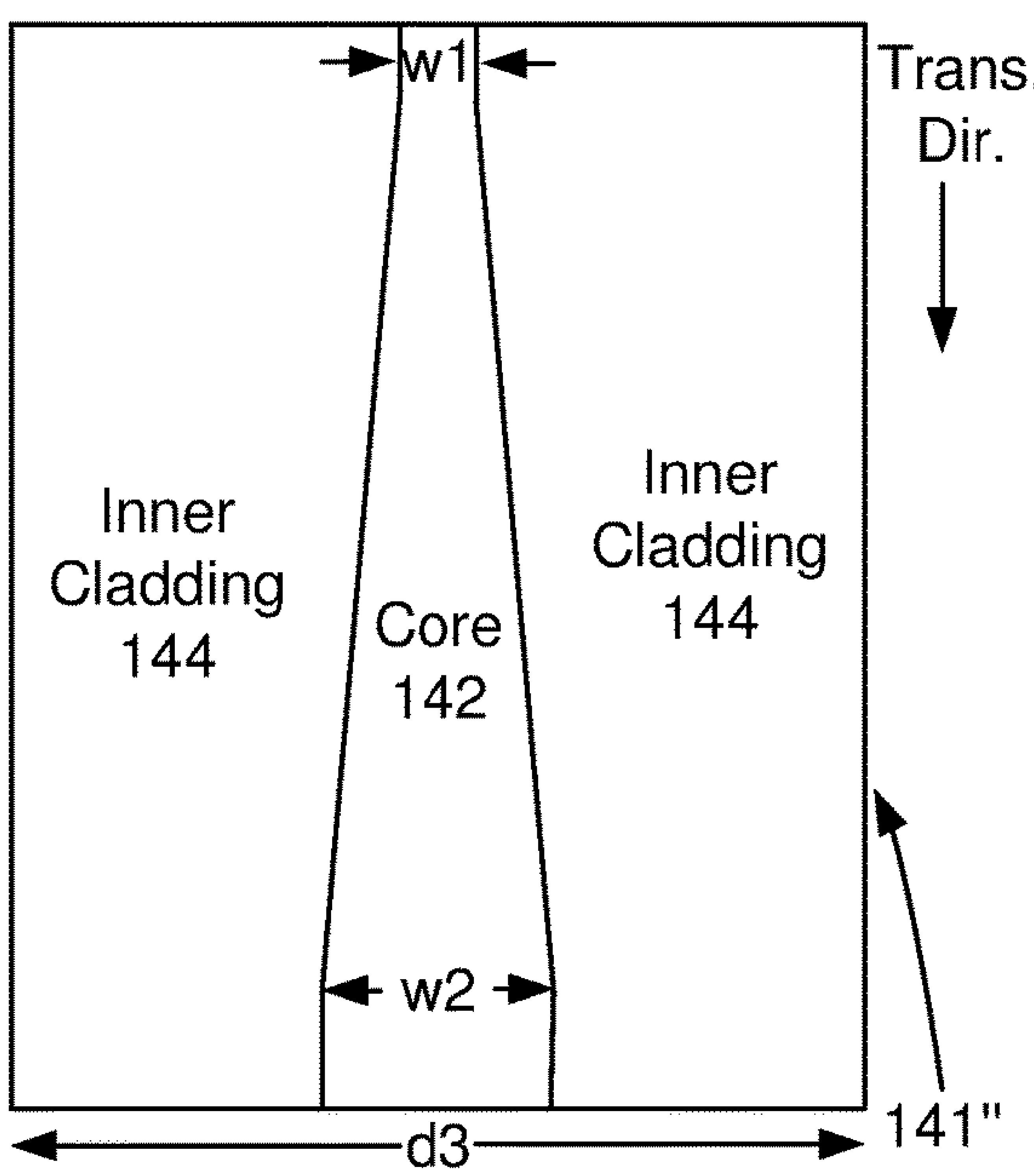


FIG. 3A

140"/141"

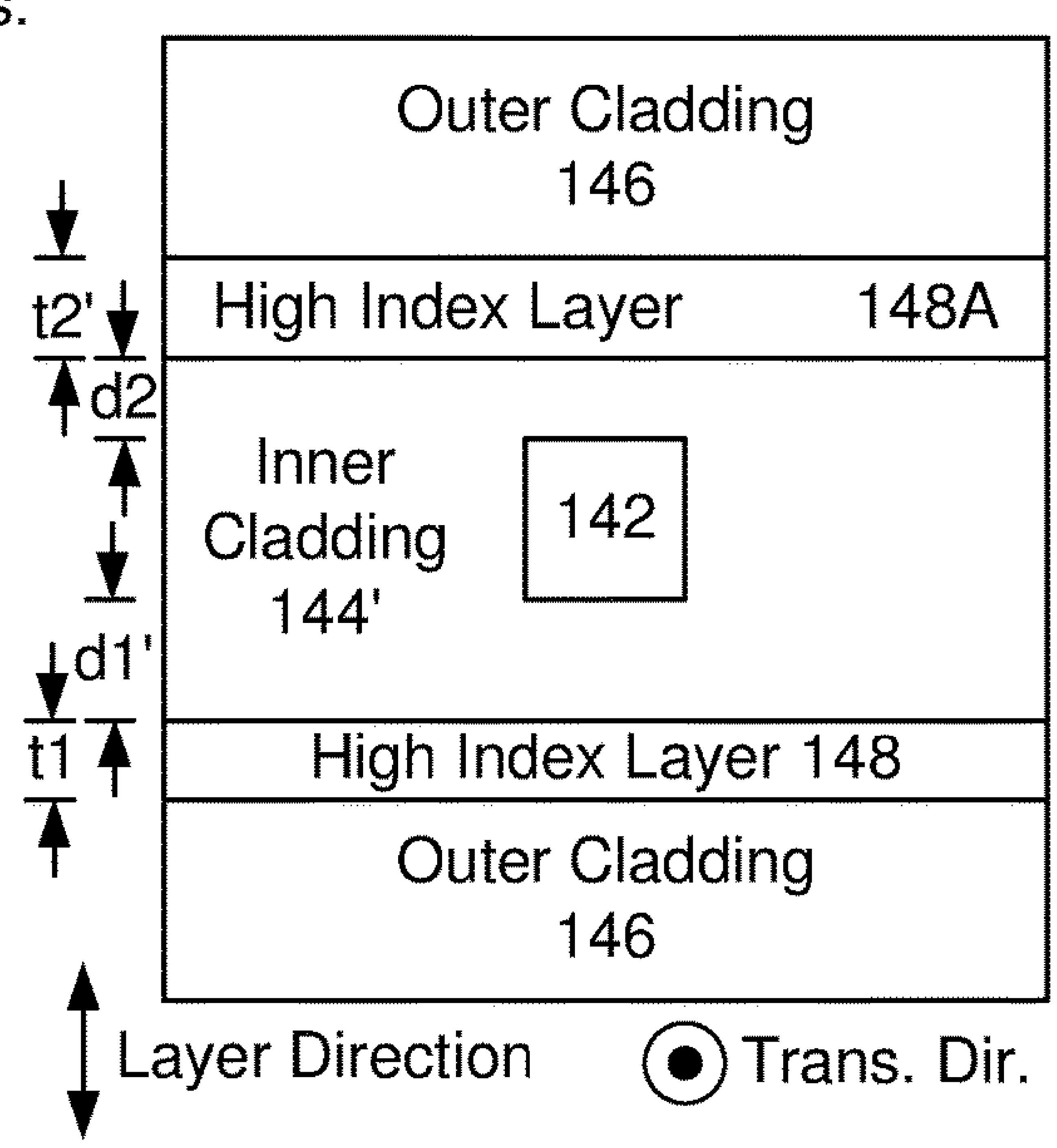


FIG. 3B

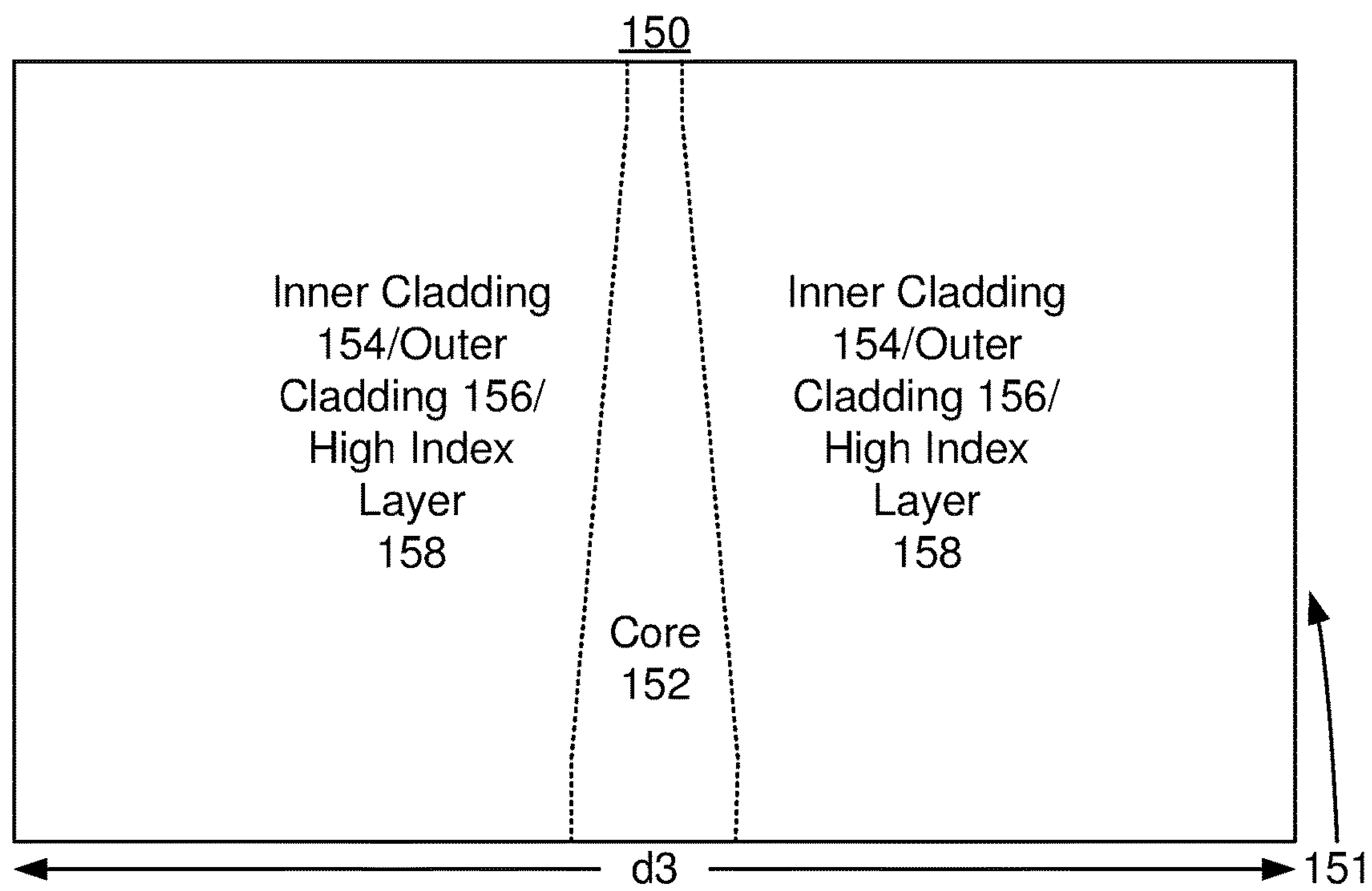

150
Inner Cladding 154/Outer Cladding 156/ High Index Layer 158
Inner Cladding 154/Outer Cladding 156/ High Index Layer 158
Core 152
d3
151

FIG. 4

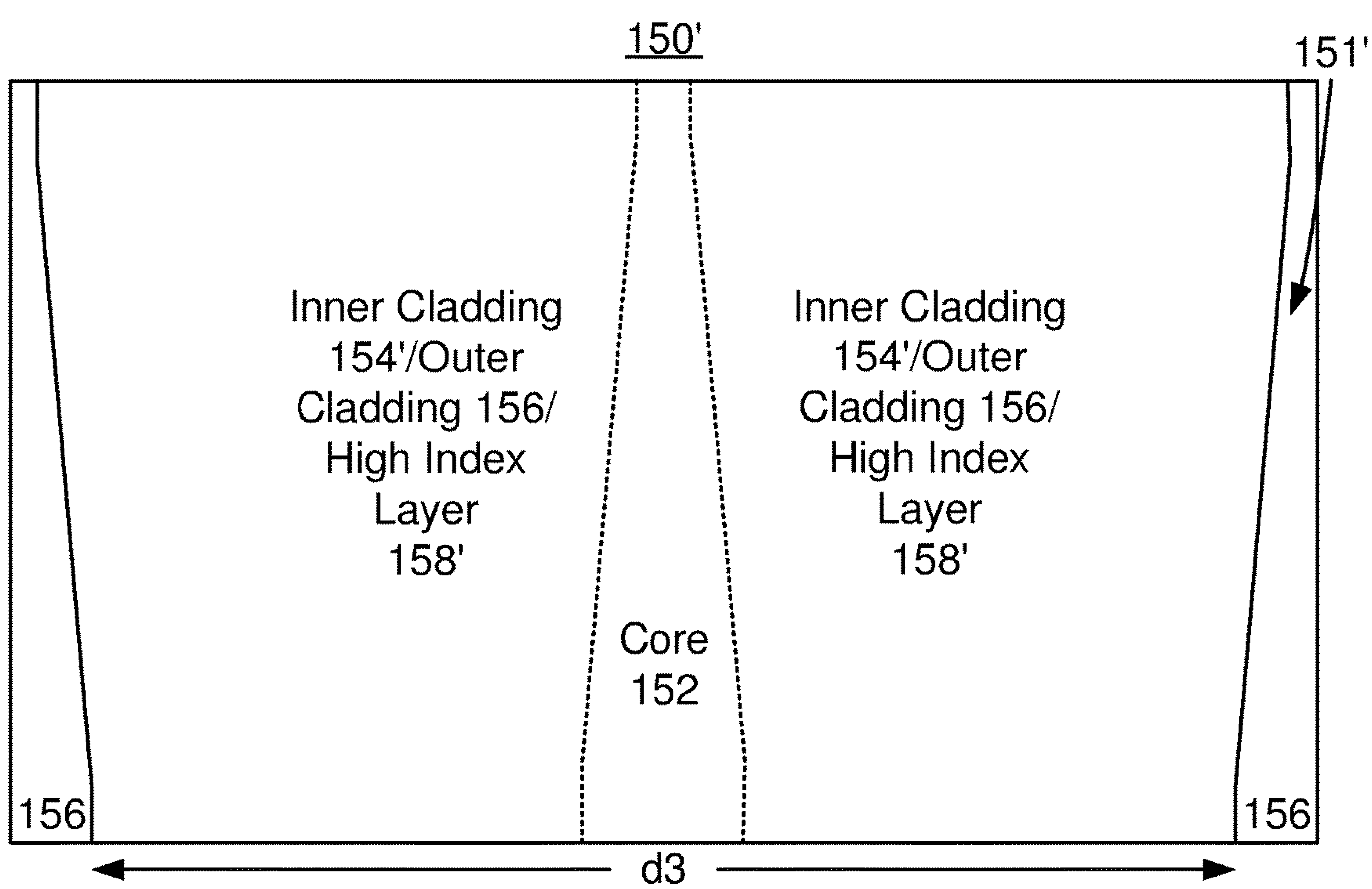

150'
151'
Inner Cladding 154'/Outer Cladding 156/ High Index Layer 158'
Inner Cladding 154'/Outer Cladding 156/ High Index Layer 158'
Core 152
156
156
d3

FIG. 5

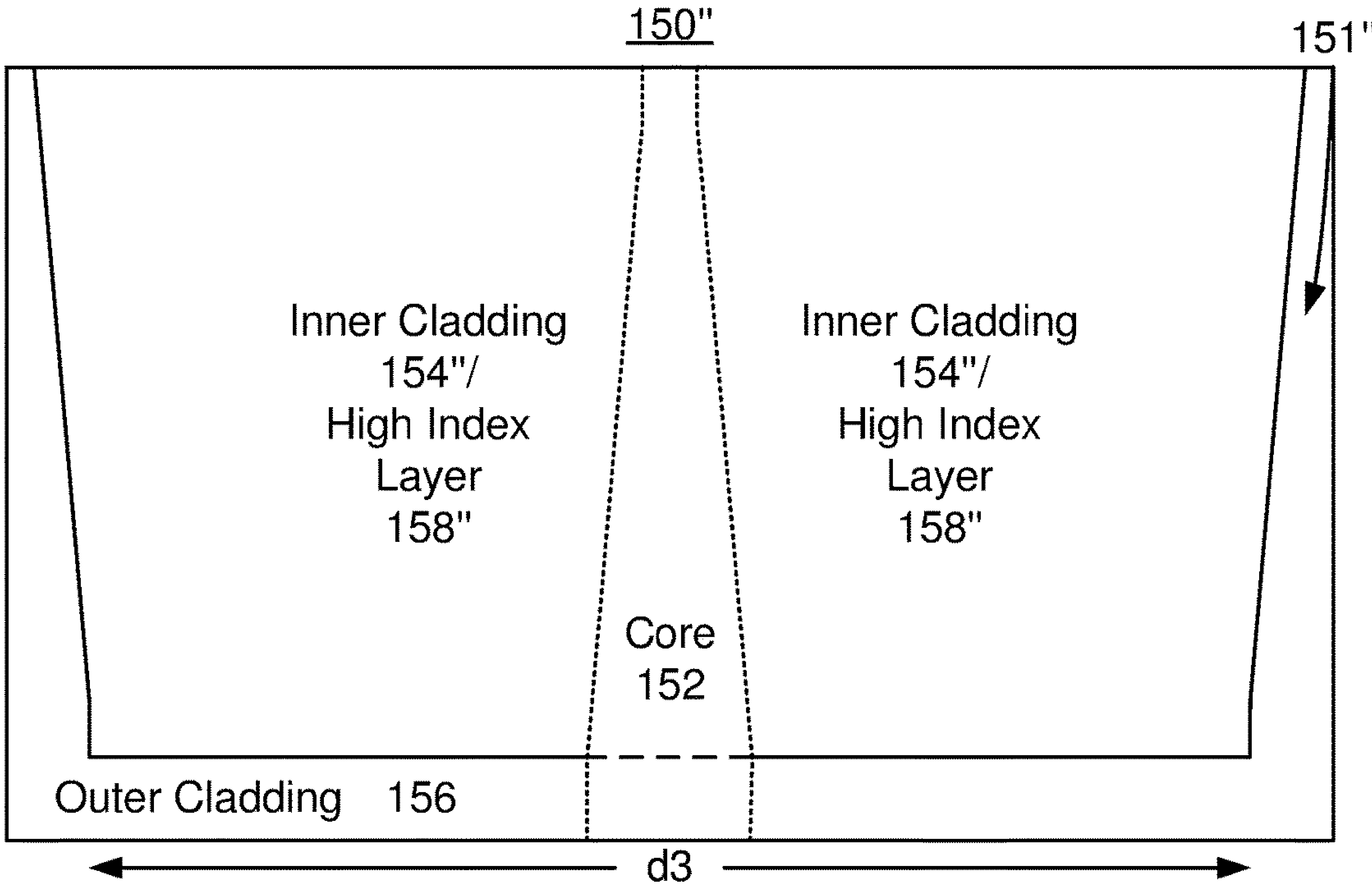

150"
151"
Inner Cladding
154"/
High Index
Layer
158"
Inner Cladding
154"/
High Index
Layer
158"
Core
152
Outer Cladding 156
d3

FIG. 6

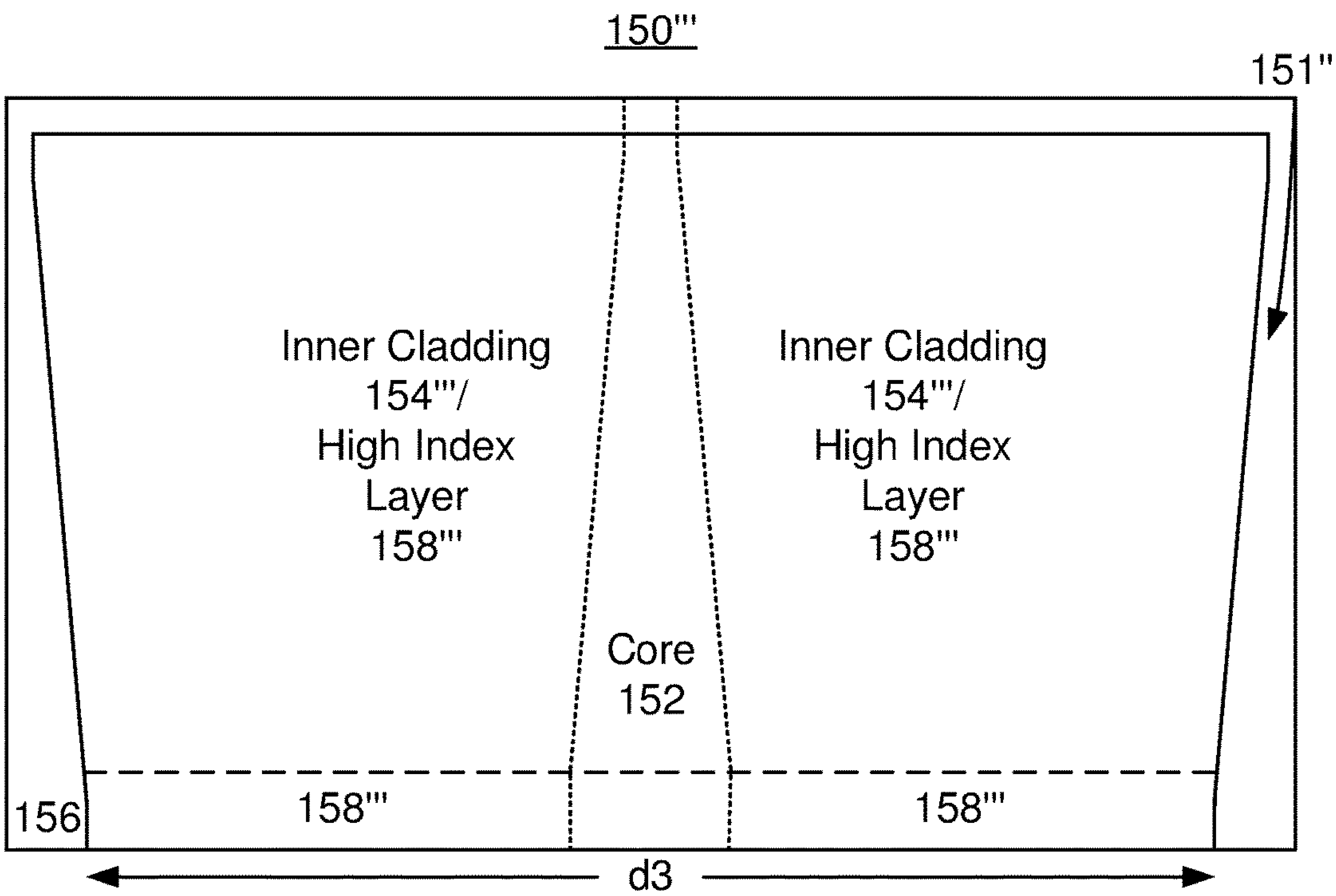

150'''
151'''
Inner Cladding
154'''/
High Index
Layer
158'''
Inner Cladding
154'''/
High Index
Layer
158'''
Core
152
156
158'''
158'''
d3

FIG. 7

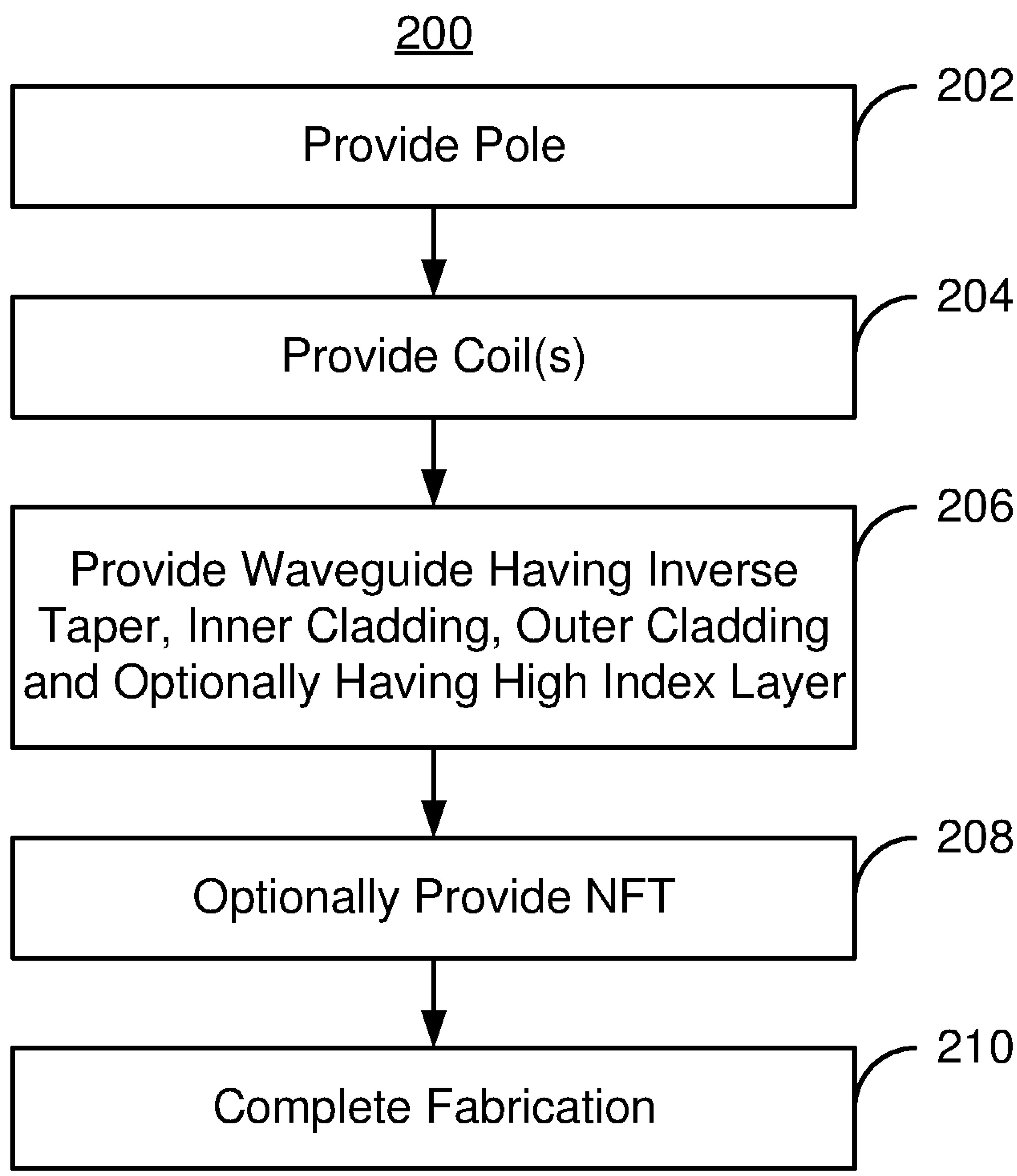

200
Provide Pole
202
Provide Coil(s)
204
Provide Waveguide Having Inverse Taper, Inner Cladding, Outer Cladding and Optionally Having High Index Layer
206
Optionally Provide NFT
208
Complete Fabrication
210

FIG. 8

HEAT ASSISTED MAGNETIC RECORDING WRITE APPARATUS HAVING AN INVERSE TAPERED WAVEGUIDE

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation application of U.S. application Ser. No. 15/216,639, filed on Jul. 21, 2016, now U.S. Pat. No. 9,697,854, the entirety of which is incorporated by reference herein.

BACKGROUND

A heat assisted magnetic recording (HAMR) write apparatus typically includes at least a waveguide, a near-field transducer (NFT), a main pole and a coil for energizing the main pole. The HAMR write apparatus uses light, or energy, received from a laser in order to write to a magnetic recording media. Light from the laser is incident on and coupled into the waveguide. Light is guided by the waveguide to the NFT near the air-bearing surface (ABS). The NFT focuses the light to magnetic recording media, such as a disk. This region is thus heated. The main pole is energized and field from the pole tip is used to write to the heated portion of the recording media.

Although the HAMR write apparatus functions, improvements in performance are still desired. For example, better coupling of the laser light into the media is desirable for improved efficiency. A large waveguide mode size may be beneficial in coupling light from the laser to the waveguide. In contrast, a small, highly confined mode is desirable for efficient coupling from the waveguide to the NFT. Without more, these requirements are in opposition to each other. As a result, efficiency and performance of the HAMR writer may be adversely affected.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

FIGS. **1**A, **1**B, **1**C and **1**D are diagrams depicting side, close up side, plan and MFS cut views of an exemplary embodiment of a portion of a HAMR data storage device.

FIGS. **2**A and **2**B are diagrams depicting plan and MFS cut views of another exemplary embodiment of a portion of a HAMR data storage device.

FIGS. **3**A and **3**B are diagrams depicting plan and MFS cut views of another exemplary embodiment of a portion of a HAMR data storage device.

FIG. **4** is a diagram depicting a plan view of another exemplary embodiment of a portion of a HAMR data storage device.

FIG. **5** is a diagram depicting a plan view of another exemplary embodiment of a portion of a HAMR data storage device.

FIG. **6** is a diagram depicting a plan view of another exemplary embodiment of a portion of a HAMR data storage device.

FIG. **7** is a diagram depicting a plan view of another exemplary embodiment of a portion of a HAMR data storage device.

FIG. **8** is a flow chart depicting an exemplary embodiment of a method for fabricating a HAMR write apparatus.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGS. **1**A, **1**B, **1**C and **1**D depict side, close up side, plan and media-facing surface (MFS) cut views of an exemplary embodiment of a portion of a heat-assisted magnetic recording (HAMR) data storage device **100**. The close up side view in FIG. **1**B is shown from the same direction as in FIG. **1**A. The plan view shown in FIG. **1**C is taken along a surface perpendicular to the side view shown in FIG. **1**A. The MFS cut view shown in FIG. **1**D is taken along a surface parallel to the MFS. For clarity, FIGS. **1**A, **1**B, C and **1**D are not to scale. The HAMR data storage device **100** shown is a disk drive. However, other data storage devices may be used. For simplicity not all portions of the HAMR data storage device **100** are shown. In addition, although the HAMR data storage device **100** is depicted in the context of particular components other and/or different components may be used. For example, circuitry used to drive and control various portions of the HAMR data storage device **100** is not shown. For simplicity, only single components are shown. However, multiples of each component and their sub-components, might be used.

The HAMR data storage device **100** includes media **102**, a slider **110**, a laser subassembly **120** and a HAMR write apparatus **130**. Although not shown, the slider **110**, and thus the laser assembly **120** and HAMR write apparatus **130** are generally attached to a suspension. The laser assembly **120** includes a laser **124** and a submount **122**. The submount **122** is a substrate to which the laser **124** may be affixed for improved mechanical stability, heat sinking, ease of manufacturing and better robustness. The laser **124** may be a chip such as a laser diode or other laser. Although not shown, the laser subassembly **120** may include a photodetector which samples light tapped from the waveguide **140** of the HAMR write apparatus **130**. In some embodiments the laser **124** may be located in a position other than on the slider, but still optically coupled to the waveguide **140**.

The HAMR write apparatus **130** is fabricated on the slider **110** and includes a MFS proximate to the media **102** during use. Because the data storage device **100** is a disk drive, the MFS shown is an air-bearing surface (ABS). In some embodiments, the MFS is a different gas-bearing surface, e.g. helium. In general, the HAMR write apparatus **130** and a read apparatus are present in the HAMR data storage device **100**. However, for clarity, only the HAMR write apparatus **130** is shown. The HAMR write apparatus **130** includes coil(s) **132**, write pole **134**, an optional near-field transducer (NFT) **136** and a waveguide **140**.

The pole **134** writes to a region of the media **102**. The pole **134** is magnetic and may have a high saturation magnetization in excess of 2.0 T. In some embodiments, the saturation magnetization of the pole **134** may be at least 2.4 T. The coils **132** may form a single helical (toroidal) coil or may be a spiral, or pancake, coil. Although depicted as a single layer, multiple layers may be used for the coils **132**. Further, although shown as a single coil, multiple coils may be used. The coils **132** are used to energize the pole **134**. Although a particular geometry is shown for the pole **134** and coil(s) **132**, in another embodiment, other geometries are possible.

The waveguide **140** is optically coupled with the laser **124** and carries light energy from the laser **124** toward the MFS. The waveguide **140** has an entrance further from the MFS and bottom that is both closer to the MFS and wider than the entrance. In some embodiments, the waveguide **140** is butt coupled to the laser **124**. Thus, the entrance of the waveguide **140** may be at the back side of the slider **110**. The waveguide **140** also includes a mode converter **141**, which is used to improve confinement of the mode of light being directed by the waveguide **140**. The mode converter **141** is more clearly shown in FIGS. **1**B, **1**C and **1**D. The mode converter **141** has a core **142**, inner cladding **144**, outer cladding **146** and at least one high index layer **148**. The inner cladding **144** is between the core **142** and the outer cladding **146**. In addition, the high index layer **148** is between a portion of the inner cladding **144** and the outer cladding **146**.

The waveguide **140** and mode converter **141** primarily direct light using the core **142**. Therefore, the width and thickness in the layer direction of the core **142** may be considered to be interchangeable with the width and depth of the waveguide **140** and mode converter **141** unless otherwise specified. The sides of the mode converter **141** diverge in the transmission direction (e.g. toward the MFS) and perpendicular to the layer direction (shown in FIGS. **1**B and **1**D). Stated differently, the mode converter **141** has an inverse taper. As is shown in FIG. **1**C, for example, the mode converter entrance has a width w**1**, while the bottom has a width, w**2**. The bottom width is wider than the entrance. In the embodiment shown, the thickness of the core **142** does not change along the transmission direction. However, in other embodiments, the thickness of the core **142**/mode converter **141** may vary along the transmission direction.

The core **142**, inner cladding **144**, outer cladding **146** and high index layer **148** are optical materials having various indices of refraction. The core **142** has a core index of refraction. The outer cladding **146** has an outer cladding index of refraction that is less than the core index of refraction. The inner cladding **144** has an inner cladding index of refraction that is not greater than the outer cladding index of refraction. In general, the inner cladding index of refraction is less than the outer cladding index of refraction. The high index layer **148** has a high index of refraction greater than the outer cladding index of refraction. For example, the core **142** may be formed of Ta_2O_5 having an index of refraction of approximately 2.1. The high index layer **148** may also be formed of Ta_2O_5. The inner cladding **144** may be formed of amorphous silica having an index of refraction of approximately 1.5. In some embodiments, the outer cladding **146** may be made of amorphous alumina having an index of refraction of 1.7. The outer cladding index of refraction is higher than the inner cladding index of refraction. In other embodiments, the outer cladding **146** may also be formed of amorphous silica or the inner cladding **144** may be made of amorphous alumina. In such embodiments, the inner cladding index of refraction is substantially the same as the outer cladding index of refraction. However, the outer cladding index of refraction is generally desired to greater than the inner cladding index of refraction. Although described in the context of tantalum oxide, alumina and silica, other and/or additional material(s) may be used in forming the waveguide **140**.

The thickness of the inner cladding **144**, the separation between the core **142** and the outer cladding **146** (d**2**), separation between the core **142** and high index layer **148** (d**1**), the width of the inner cladding **144** (d**3**), the thickness of the core in the layer direction and the thickness of the high index layer (t**1**) are also depicted in FIGS. **1**C and **1**D. In general, these dimensions are desired to be configured based upon the characteristic wavelength of the laser **124**. The laser **124** may be described as producing light of the characteristic wavelength. The actual wavelength of light produced by the laser **124** during operation may vary slightly based on temperature and other operating parameters.

In some embodiments, the core **142** is relatively thin. For example, the core **142** may have a thickness that is less than the characteristic wavelength. In some embodiments, the core thickness is not more than one-third multiplied by the characteristic wavelength. Further, the width, w**1**, of the core **142** at the mode converter entrance may also be not more than one-third of the characteristic wavelength. In some embodiments, w**1** is at least one-fourth of the characteristic wavelength and not more than one-third of the characteristic wavelength. The core **142** widens as the mode converter **141** sides diverge. For example, the width, w**2**, of the bottom of the mode converter **141** may be at least one-half multiplied by the characteristic wavelength and not more than three-fourth multiplied by the characteristic wavelength. However, other widths w**1** and w**2** and core thicknesses are possible.

The inner cladding **144** extends from the core **142** in a direction perpendicular to a transmission direction and perpendicular to a layer direction a distance that is at least 1.5 multiplied by the characteristic wavelength. Thus, the width, d**3** is at least three multiplied by the characteristic wavelength. In some embodiments, d**3** is at least four multiplied by the characteristic wavelength. However, other widths of the inner cladding **144** are possible. For example, the inner cladding **144** may have a width that is significantly larger than four multiplied by the characteristic wavelength. The inner cladding **144** may also extend from the core **142** in the layer direction an amount at least 1/16 multiplied by the characteristic wavelength and not more than ¼ multiplied by the characteristic wavelength. Thus d**1** and d**2** may each be at least 1/16 multiplied by the characteristic wavelength and not more than ¼ multiplied by the characteristic wavelength. Other values of d**1** and d**2** are possible. In the embodiment shown, d**1** and d**2** are equal. However, in other embodiments, d**1** and d**2** may differ.

Because the inner cladding **144** may extend at least 1/16 multiplied by the characteristic wavelength and not more than ¼ multiplied by the characteristic wavelength, the high index layer **148** may also be this distance from the core **142**. Note that although shown below the core **142**, the high index layer **148** may be located above the core in another embodiment. The high index layer **148** may be desired to extend as far as the inner cladding **144** in the direction perpendicular to the layer and transmission directions. Stated differently, the high index layer **148** may have a width of d**3** in this direction. Thus, the width of the high index layer **148**, d**3**, is at least three multiplied by the characteristic wavelength. In some embodiment, this width is at least four multiplied by the characteristic wavelength. However, other widths of the high index layer **148** are possible. The thickness, t**1**, of the high index layer **148** may be at least 1/16 multiplied by the characteristic wavelength and not more than ¼ multiplied by the characteristic wavelength. Other values of t**1** are possible. Further, the high index layer **148** may extend along the core **142** in the transmission direction for all of the mode converter **141**. In such embodiments, the high index layer **148** extends along the core **142** in the transmission direction at least as long as a mode converter length.

Thus, the waveguide **140** include a mode converter **141** having diverging sides. The mode converter **141** also includes a core **142**, inner cladding **144**, outer cladding **146** and high index layer **148**. In some embodiments, the inner cladding **144**, outer cladding **146** and/or high index layer **148** may terminate at or near the end of the mode converter **141**. In other embodiments, the inner cladding **144**, outer cladding **146** and/or high index layer **148** may extend along the entire waveguide **140**. The core **142** extends along all of the waveguide **140**. The waveguide **140** thus couples light energy from the laser **124**, reduces the mode size using the mode converter **141** and directs the energy toward the MFS.

The NFT 136 couples a portion of the energy from the waveguide 140 to the media 102. The NFT 136 resides at or near the MFS and utilizes surface plasmons to focus the light to the magnetic recording media 102. The NFT 136 couples the energy of the surface plasmons efficiently into the recording medium layer of the media 102 with a confined spot which is much smaller than the optical diffraction limit. This confined spot can rapidly heat the recording medium layer to near or above the Curie point of the media 102. High density bits can be written on a high coercivity medium with the pole 134 energized by the coils 132 to a modest magnetic field. In the embodiment shown, the NFT 136 occupies part of the MFS and may be formed of Au or an Au alloy. In an alternate embodiment, the NFT 136 might be recessed from the MFS. The NFT 136 might be formed of another material and/or have another shape in other embodiments.

The HAMR data storage device 100 may exhibit improved performance. The mode converter 141 having a core 142 with diverging sides can efficiently reduce the size of the mode carried by the waveguide. Use of the inner cladding 144 that may have a lower inner cladding index of refraction allows the mode expansion peak, at which optical coupling efficiency is higher, to occur for higher core 142 widths (dimension perpendicular to transmission and layer directions). Stated differently, the mode may be more efficiently reduced in size while maintaining power at higher widths of the core 142. Consequently, the aspect ratio, or height divided by width of the core 142 is decreased. A waveguide 140 having a lower aspect ratio may be easier to manufacture. The use of the inner cladding 144 such as amorphous silica may also improve the reliability of the HAMR write apparatus 130. The high index layer 148 may operate to stretch the optical mode in the layer direction (perpendicular to transmission direction). This allows the input mode of the laser 124 to be better matched by the waveguide 140. Efficiency of the waveguide 140 may thus be improved. As a result, the waveguide 140 is better able to couple light energy in from the laser 124 and provide energy to the NFT 136. More energy is made available for heating the media 102. Performance, manufacturability and reliability of the HAMR write apparatus 130 and the data storage device 100 may, therefore, be enhanced.

FIGS. 2A and 2B depict plan and MFS cut views of another exemplary embodiment of a portion of the HAMR data storage device 100' and write apparatus 130'. For clarity, FIGS. 2A-2B are not to scale. For simplicity not all portions of the HAMR data storage device 100' are shown. In addition, although the HAMR disk drive 100' is depicted in the context of particular components other and/or different components may be used. Further, the arrangement of components may vary in different embodiments. The HAMR disk drive 100' is analogous to the HAMR disk drive 100. Consequently, similar components have analogous labels. The HAMR write apparatus 130' thus includes waveguide 140', pole (not shown in FIGS. 2A-2B), coil(s) (not shown in FIGS. 2A-2B) and optional NFT (not shown in FIGS. 2A-2B) that are analogous to the waveguide 140, pole 134, coil(s) 132 and optional NFT 136, respectively.

The waveguide 140' includes a mode converter 141' and a core 142 that are analogous to the mode converter 141 and core 142 of the waveguide 140. Thus, the core 142, inner cladding 144 and outer cladding 146 are analogous to the core 142, inner cladding 144 and outer cladding 146 of the waveguide 140. The dimensions d1, d2, d3, t1, w1 and w2 are analogous to those described above with respect to the waveguide 140.

The mode converter 141' includes high index layer 148. In addition, a second high index layer 148A is also provided. The high index layer 148A may be formed of the same or different material(s) as the high index layer 148. However, the high index layer 148A still has a high index of refraction that is greater than the outer cladding index of refraction and the inner cladding index of refraction. In some embodiments the high index layer 148A has a high index of refraction that is not less than the core index of refraction. For example, the high index layer 148A may also be formed of Ta_2O_5. The high index layers 148 and 148A are shown as being the same distance from the core 142. However, in other embodiments, the high index layers 148 and 148A may be different distance from the core 142. The high index layer 148A has a thickness t2 that is at least 1/16 multiplied by the characteristic wavelength and not more than ¼ multiplied by the characteristic wavelength. The thickness t2 may be the same as or different from the thickness t1. Further, the high index layer 148A may extend along the core 142 in the transmission direction for at least the length of the mode converter 141.

The HAMR data storage device 100' and write apparatus 130' may share the benefits of the HAMR data storage device 100 and write apparatus 130, respectively. The core 142 may have a lower aspect ratio while maintaining the ability to couple in light from the laser 124 and reduce the mode size. Efficiency and fabrication of the waveguide 140' may thus be improved. Use of a lower index of refraction inner cladding 144 may also improve reliability of the HAMR data storage device 100' and write apparatus 130'. More energy may made available for heating the media 102. Performance, manufacturability and reliability of the HAMR write apparatus 130' and the HAMR data storage device 100' may, therefore, be enhanced.

FIGS. 3A and 3B depict plan and MFS cut views of another exemplary embodiment of a portion of the HAMR data storage device 100" and write apparatus 130". For clarity, FIGS. 3A-3B are not to scale. For simplicity not all portions of the HAMR data storage device 100" are shown. In addition, although the HAMR disk drive 100" is depicted in the context of particular components other and/or different components may be used. Further, the arrangement of components may vary in different embodiments. The HAMR disk drive 100" is analogous to the HAMR disk drive(s) 100 and/or 100'. Consequently, similar components have analogous labels. The HAMR write apparatus 130" thus includes waveguide 140", pole (not shown in FIGS. 3A-3B), coil(s) (not shown in FIGS. 3A-3B) and optional NFT (not shown in FIGS. 3A-3B) that are analogous to the waveguide 140, pole 134, coil(s) 132 and optional NFT 136, respectively.

The waveguide 140" includes a mode converter 141" and a core 142 that are analogous to the mode converter 141 and core 142 of the waveguide 140. Thus, the core 142, inner cladding 144', outer cladding 146, high index layer 148 and high index layer 148A are analogous to the core 142, inner cladding 144, outer cladding 146, high index layer 148 and high index layer 148A of the waveguide(s) 140 and 140'. The dimensions d1', d2, d3, t1, t2', w1 and w2 are analogous to the dimensions d1, d2, d3, t1, t2, w1 and w2 for the waveguide(s) 140 and/or 140'.

The high index layer 148A is a different distance from the core 142 than the high index layer 148. In other words, d1' is different from d2. In the embodiment shown, d1' is greater than d2. In other embodiments, d1' might be less than d2.

Similarly, the thicknesses of the high index layers **148** and **148**A are different (t**1**≠t**2**'). In the embodiment shown, t**2**' is greater than t**1**. However, in other embodiments, t**2**' may be less than or equal to t**1**.

The HAMR data storage device **100**" and write apparatus **130**" may share the benefits of the HAMR data storage device **100**/**100**' and write apparatus **130**/**130**', respectively. The core **142** may have a lower aspect ratio while maintaining the ability to couple in light from the laser **124** and reduce the mode size. Efficiency and fabrication of the waveguide **140**" may thus be improved. Use of a lower index of refraction inner cladding **144**' may also improve reliability of the HAMR data storage device **100**" and write apparatus **130**". More energy may made available for heating the media **102**. Performance, fabrication and reliability of the HAMR write apparatus **130**" and the HAMR data storage device **100**" may, therefore, be enhanced.

FIG. **4** depicts a plan view of another exemplary embodiment of a portion of a waveguide **150** for a HAMR write apparatus such as the HAMR write apparatus **130**, **130**' and/or **130**". Thus, the waveguide **150** may be used in the HAMR data storage device **100**, **100**' and/or **100**". For clarity, FIG. **4** is not to scale. For simplicity not all portions of the waveguide **150** are shown. In addition, although the waveguide **150** is depicted in the context of particular components other and/or different components may be used. Further, the arrangement of components may vary in different embodiments.

The waveguide **150** includes a mode converter **151**, a core **152**, inner cladding **154**, outer cladding **156** and one or more high index layer(s) **158** that are analogous to the mode converter **141**/**141**'/**141**", core **142**, inner cladding **144**/**144**' and high index layer(s) **148**/**148**A of the waveguide(s) **140**, **140**' and/or **140**". The dimensions and indices of refraction of the waveguide **150** are analogous to the dimensions d**1**/d**1**', d**2**, d**3**, t**1**, t**2**/t**2**', w**1** and w**2** and indices of refraction for the waveguide(s) **140**, **140**' and/or **140**".

The high index layer(s) **158** and inner cladding **154** are shown as extending a distance d**3** in the side direction perpendicular to the transmission and layer directions. However, in some embodiments, the high index layer(s) **158** and inner cladding **154** may extend further sideways. In general, as long as the high index layer(s) **158** and inner cladding **154** extend at least the distance d**3** in the side direction, the actual width of these layers **154** and **158** becomes less important. For example, the high index layer(s) **158** and inner cladding **154** may extend to the edges of the slider.

A HAMR data storage device and HAMR write apparatus using the waveguide **150** may share the benefits of the HAMR data storage device **100**/**100**'/**100**" and write apparatus **130**/**130**'/**130**", respectively. The core **152** may have a lower aspect ratio while maintaining the ability to couple in light from the laser and reduce the mode size. Efficiency and fabrication of the waveguide **150** may thus be improved. Use of the lower index of refraction inner cladding **154** may also improve reliability of the HAMR data storage device and write apparatus using the waveguide **150**. More energy may made available for heating the media. Performance and reliability of the HAMR write apparatus and the HAMR data storage device in which the waveguide **150** is used may, therefore, be enhanced.

FIG. **5** depicts a plan view of another exemplary embodiment of a portion of a waveguide **150**' for a HAMR write apparatus such as the HAMR write apparatus **130**, **130**' and/or **130**". Thus, the waveguide **150**' may be used in the HAMR data storage device **100**, **100**' and/or **100**". The waveguide **150**' is analogous to the waveguide **150**. For clarity, FIG. **5** is not to scale. For simplicity not all portions of the waveguide **150**' are shown. In addition, although the waveguide **150**' is depicted in the context of particular components other and/or different components may be used. Further, the arrangement of components may vary in different embodiments.

The waveguide **150**' includes a mode converter **151**', a core **152**, inner cladding **154**', outer cladding **156** and one or more high index layer(s) **158**' that are analogous to the mode converter **151**, core **152**, inner cladding **154**, outer cladding **156** and high index layer(s) **158** of the waveguide **150**. The dimensions and indices of refraction of the waveguide **150**' are analogous to the dimensions d**1**/d**1**', d**2**, d**3**, t**1**, t**2**/t**2**', w**1** and w**2** and indices of refraction for the waveguide(s) **140**, **140**' and/or **140**".

The high index layer(s) **158**' and inner cladding **154**' are shown as extending a distance d**3** in the side direction perpendicular to the transmission and layer directions near the bottom of the mode converter **151**'. However, the high index layer(s) **158**' and inner cladding **154**' are patterned to be forward tapered. Consequently, the outer cladding **156** may extend further sideways than the inner cladding **154**' and high index layer(s) **158**'. In other embodiments, the inner cladding **158**' and/or high index layer(s) **158**' may be inversely tapered in a manner analogous to the core.

A HAMR data storage device and HAMR write apparatus using the waveguide **150**' may share the benefits of the HAMR data storage device **100**/**100**'/**100**" and write apparatus **130**/**130**'/**130**", respectively. The core **152** may have a lower aspect ratio while maintaining the ability to couple in light from the laser and reduce the mode size. Efficiency and fabrication of the waveguide **150**' may thus be improved. Use of the lower index of refraction inner cladding **154**' may also improve reliability of the HAMR data storage device and write apparatus using the waveguide **150**'. More energy may made available for heating the media. Performance and reliability of the HAMR write apparatus and the HAMR data storage device in which the waveguide **150**' is used may be enhanced.

FIG. **6** depicts a plan view of another exemplary embodiment of a portion of a waveguide **150**" for a HAMR write apparatus such as the HAMR write apparatus **130**, **130**' and/or **130**". Thus, the waveguide **150**" may be used in the HAMR data storage device **100**, **100**' and/or **100**". The waveguide **150**" is analogous to the waveguide(s) **150** and/or **150**'. For clarity, FIG. **6** is not to scale. For simplicity not all portions of the waveguide **150**" are shown. In addition, although the waveguide **150**" is depicted in the context of particular components other and/or different components may be used. Further, the arrangement of components may vary in different embodiments.

The waveguide **150**" includes a mode converter **151**", a core **152**, inner cladding **154**", outer cladding **156** and one or more high index layer(s) **158**" that are analogous to the mode converter **151**/**151**', core **152**, inner cladding **154**/**154**', outer cladding **156** and high index layer(s) **158**/**158**' of the waveguide **150**/**150**'. The dimensions and indices of refraction of the waveguide **150**" are analogous to the dimensions d**1**/d**1**', d**2**, d**3**, t**1**, t**2**/t**2**', w**1** and w**2** and indices of refraction for the waveguide(s) **140**, **140**' and/or **140**".

The high index layer(s) **158**" and inner cladding **154**" are shown as extending a distance d**3** in the side direction perpendicular to the transmission and layer directions near the bottom of the mode converter **151**". The inner cladding **154**" and high index layer(s) **158**" are also forward tapered. However, the inner cladding **154**" and high index layer(s) **158**" do not extend in the transmission direction along the entire waveguide **150"**. Consequently, the outer cladding **156** may extend further sideways and along the transmission direction than the inner cladding **154"** and high index layer(s) **158"**.

A HAMR data storage device and HAMR write apparatus using the waveguide **150"** may share the benefits of the HAMR data storage device **100/100'/100"** and write apparatus **130/130'/130"**, respectively. The core **152** may have a lower aspect ratio while maintaining the ability to couple in light from the laser and reduce the mode size. Efficiency and fabrication of the waveguide **150"** may thus be improved. Use of the lower index of refraction inner cladding **154"** may also improve reliability of the HAMR data storage device and write apparatus using the waveguide **150"**. More energy may made available for heating the media. Performance and reliability of the HAMR write apparatus and the HAMR data storage device in which the waveguide **150"** is used may be enhanced.

FIG. **7** depicts a plan view of another exemplary embodiment of a portion of a waveguide **150'"** for a HAMR write apparatus such as the HAMR write apparatus **130**, **130'** and/or **130"**. Thus, the waveguide **150'"** may be used in the HAMR data storage device **100**, **100'** and/or **100"**. The waveguide **150'"** is analogous to the waveguide(s) **150**, **150'** and/or **150"**. For clarity, FIG. **7** is not to scale. For simplicity not all portions of the waveguide **150'"** are shown. In addition, although the waveguide **150'"** is depicted in the context of particular components other and/or different components may be used. Further, the arrangement of components may vary in different embodiments.

The waveguide **150'"** includes a mode converter **151'"**, a core **152**, inner cladding **154'"**, outer cladding **156** and one or more high index layer(s) **158'"** that are analogous to the mode converter **151/151'/151"**, core **152**, inner cladding **154**, outer cladding **156/156'/156"** and high index layer(s) **158/158'/158"** of the waveguide **150/150'/150"**. The dimensions and indices of refraction of the waveguide **150'"** are analogous to the dimensions d**1**/d**1'**, d**2**, d**3**, t**1**, t**2**/t**2'**, w**1** and w**2** and indices of refraction for the waveguide(s) **140**, **140'** and/or **140"**.

The high index layer(s) **158'"** and inner cladding **154'"** are shown as extending a distance d**3** in the side direction perpendicular to the transmission and layer directions near the bottom of the mode converter **151'"**. The inner cladding **154'"** and high index layer(s) **158'"** also have a forward taper. The inner cladding **154'"** and high index layer(s) **158'"** do not extend in the transmission direction along the entire waveguide **150'"**. Consequently, the outer cladding **156** may extend further sideways and along the transmission direction than the inner cladding **154'"** and high index layer(s) **158'"**. In addition, the inner cladding **154'"** and high index layer(s) **158'"** extend different distances along the core **152**.

A HAMR data storage device and HAMR write apparatus using the waveguide **150'"** may share the benefits of the HAMR data storage device **100/100'/100"** and write apparatus **130/130'/130"**, respectively. The core **152** may have a lower aspect ratio while maintaining the ability to couple in light from the laser and reduce the mode size. Efficiency and fabrication of the waveguide **150'"** may thus be improved. Use of the lower index of refraction inner cladding **154'"** may also improve reliability of the HAMR data storage device and write apparatus using the waveguide **150'"**. More energy may made available for heating the media. Performance and reliability of the HAMR write apparatus and the HAMR data storage device in which the waveguide **150'"** is used may be enhanced.

Various features of the HAMR write apparatus, waveguide, and mode converter are highlighted in FIGS. **1**A-**7**. One of ordinary skill in the art will readily recognize that one or more of these features may be combined in manners not explicitly described herein.

FIG. **8** is a flow chart depicting an exemplary embodiment of a method **200** for fabricating a HAMR write apparatus. The method **200** may be used in fabricating data storage devices such as the disk drives **100**, **100'** and/or **100"** using one or more of the features of the waveguides **140**, **140'**, **140"**, **150**, **150'**, **150"** and/or **150'"**, though other writers might be so fabricated. For clarity, the method **200** is described in the context of the HAMR data storage device **100** depicted in FIGS. **1**A-**1**D. For simplicity, some steps may be omitted, performed in another order, interleaved and/or combined. The HAMR data storage device being fabricated may include a write apparatus and a read apparatus (not shown) and resides on a slider. For simplicity, however, fabrication of the read apparatus is not discussed. The method **200** is also described in the context of forming a single write apparatus. However, the method **200** may be used to fabricate multiple write apparatus(es) at substantially the same time. The method **200** and system are also described in the context of particular layers. However, in some embodiments, such layers may include multiple sublayers. The method **200** also may commence after formation of other portions of the data storage device.

A pole **134** is formed, via step **202**. Step **202** may include multiple substeps such as forming a trench for the main pole in a nonmagnetic layer, plating the high saturation magnetization material(s) for the main pole and planarizing these materials. At least one coil **132** for energizing the main pole is provided, via step **204**. Step **204** generally includes multiple deposition and removal steps to form the coil. The coil **132** may be a spiral coil, a toroidal coil or have another shape.

The waveguide **140** is provided, via step **206**. Thus, waveguide is configured so that it may be optically coupled with the laser and direct a portion of the laser's energy toward the MFS. The waveguide **140** formed in step **206** includes a mode converter **141** having an inverse taper. Thus, the sides of the core **142**/mode converter **141** diverge. The mode converter **141** also has inner cladding **144**, high index layer(s) **148** and/or **148**A and outer cladding **146**. The core **142**, inner cladding **144**, outer cladding **146** and high index layer(s) **148** and/or **148**A have the indices of refraction described above. Step **206** may include depositing a portion of the outer cladding, optionally depositing a high index material, depositing part of the inner cladding and depositing a layer of core material on the inner cladding layer. Step **206** may also include patterning the core material to form the core **142** and refilling the region with additional inner cladding material. Another high index of refraction material and the remainder of the outer cladding may also be provided. Because the aspect ratio (thickness divided by width) of the core **142** is reduced, fabrication in step **206** may be simplified. For example, patterning of the core **142** and refill using the inner cladding may be more easily and better achieved. In other embodiments, other method(s) may be used to form the waveguide **140**.

The NFT **136** is optionally provided, via step **208**. Step **208** may include one or more steps of depositing metal layers and patterning the layers to form the NFT **136**. Fabrication of the HAMR writer apparatus **100** may then be completed, via step **210**.

Using the method **200**, the HAMR data storage device(s) **100**, **100'** and/or **100"** including waveguide(s) **140**, **140'**,

140", **150**, **150'**, **150"** and/or **150'"** may be fabricated. The benefit(s) of one or more of the HAMR disk drive(s) **100**, **100'** and/or **100"** may thus be achieved.

We claim:

1. A heat assisted magnetic recording write apparatus comprising:

a waveguide having an entrance distal from a media facing surface of the heat assisted magnetic recording write apparatus and an exit proximate to the media facing surface, and comprising a mode converter between the entrance and the exit,

wherein the waveguide is configured to direct energy from the entrance towards the exit via the mode converter in a transmission direction,

wherein the mode converter comprises:

a core having a first width proximate to the entrance and a second width proximate to the exit in the transmission direction, wherein the first width is less than the second width;

an inner cladding surrounding at least portions of the core and having an inner cladding index of refraction; and

an outer cladding surrounding at least portions of the inner cladding and having an outer cladding index of refraction that is different from the inner cladding index of refraction.

2. The heat assisted magnetic recording write apparatus of claim **1**, wherein the mode converter further comprises a first high index layer abutting the inner cladding below the core in a layer direction that is perpendicular to the transmission direction.

3. The heat assisted magnetic recording write apparatus of claim **2**, wherein the core has a core index of refraction, and wherein the outer cladding index of refraction is less than the core index of refraction.

4. The heat assisted magnetic recording write apparatus of claim **1**, wherein the inner cladding index of refraction is less than the outer cladding index of refraction.

5. The heat assisted magnetic recording write apparatus of claim **2**, wherein the first high index layer has a high index of refraction and the high index of refraction is greater than the outer cladding index of refraction.

6. The heat assisted magnetic recording write apparatus of claim **2**, further comprising a second high index layer above the core in the layer direction, wherein the second high index layer is between the outer cladding and the inner cladding.

7. The heat assisted magnetic recording write apparatus of claim **6**, wherein the first high index layer is separated from the core by a first distance and the second high index layer is separated from the core by a second distance, and wherein the first distance is equal to the second distance.

8. The heat assisted magnetic recording write apparatus of claim **6**, wherein the first high index layer is separated from the core by a first distance and the second high index layer is separated from the core by a second distance, and wherein the first distance is not equal to the second distance.

9. The heat assisted magnetic recording write apparatus of claim **6**, wherein a thickness of the first high index layer is substantially similar to a thickness of the second high index layer.

10. The heat assisted magnetic recording write apparatus of claim **6**, wherein a thickness of the first high index layer is different from a thickness of the second high index layer.

11. The heat assisted magnetic recording write apparatus of claim **1**, wherein the energy comprises light energy having a characteristic wavelength, and wherein the first width of the core is not more than one third of the characteristic wavelength.

12. The heat assisted magnetic recording write apparatus of claim **1**, wherein the energy comprises light energy having a characteristic wavelength, and wherein the second width of the core is at least one half of the characteristic wavelength.

13. The heat assisted magnetic recording write apparatus of claim **1**, wherein the energy comprises light energy having a characteristic wavelength, and wherein a thickness of the core in a direction perpendicular to the transmission direction is less than the characteristic wavelength.

14. A heat assisted magnetic recording write apparatus comprising:

a waveguide optically coupled to a laser of the heat assisted magnetic recording write apparatus to transfer energy from the laser towards a media facing surface in a transmission direction, the waveguide having an entrance proximate to the laser and an exit proximate to the media facing surface, and comprising a mode converter between the entrance and the exit,

wherein the mode converter comprises:

a core having sides diverging from a first width proximate to the entrance to a second width proximate to the exit in the transmission direction, the first width being less than the second width and a function of a characteristic wavelength of the energy,

an inner cladding surrounding at least a portion of the core, and

an outer cladding surrounding at least a portion of the inner cladding; and

wherein the inner cladding has a first inner cladding width in a layer direction that is perpendicular to the transmission direction and a second inner cladding width in a direction that is perpendicular to the transmission direction and the layer direction.

15. The heat assisted magnetic recording write apparatus of claim **14**, wherein the first inner cladding width is at least one sixteenth of the characteristic wavelength and the second inner cladding width is at least three times the characteristic wavelength.

16. The heat assisted magnetic recording write apparatus of claim **14**, further comprising a high index layer between the inner cladding and the outer cladding in the layer direction, and wherein a width of the high index layer in the layer direction is substantially similar to the second inner cladding width.

17. The heat assisted magnetic recording write apparatus of claim **16**, wherein the high index layer and the inner cladding are tapered such that the width of the high index layer and the second inner cladding width proximate to the entrance is greater than the width of the high index layer and the second inner cladding width proximate to the exit.

18. The heat assisted magnetic recording write apparatus of claim **16**, wherein the high index layer extends beyond the inner cladding in the transmission direction.

19. The heat assisted magnetic recording write apparatus of claim **14**, wherein the outer cladding extends beyond the second inner cladding width and beyond the inner cladding in the transmission direction.

20. A write apparatus comprising:

a waveguide having an entrance distal from a media facing surface of the write apparatus and an exit proximate to the media facing surface, and comprising a mode converter between the entrance and the exit, wherein the waveguide is configured to direct energy from the entrance towards the exit via the mode converter in a transmission direction, and

wherein the mode converter comprises:

a core having a first width proximate to the entrance and a second width that is greater than the first width proximate to the exit in the transmission direction,

an inner cladding surrounding at least a portion of the core and having an inner cladding index of refraction,

an outer cladding surrounding at least a portion of the inner cladding and having an outer cladding index of refraction that is different from the inner cladding index of refraction,

a first high index layer above the core in a direction perpendicular to the transmission direction and between the inner cladding and the outer cladding, and

a second high index layer between the inner cladding and the outer cladding below the core in the layer direction.

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